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Modeling and Analysis of IC Engine Rubber Mount using Finite Element Method and RSM

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Abstract

As the usage of vehicles has become necessary in every person's life the automotive industries are in need of reducing the vibration forces to satisfy the customer requirements. The performance and riding comfort of the automobiles are affected due to the vibrating forces. The power plants are the one of the major sources of vibration and these vibrations are caused because of the unbalanced forces from the engine. Engine mounts are identified as the one of the major sources of vibration controllers. In this investigation, modeling and analysis of an engine rubber mount are done. The mount consists of two mild steel plates and a rubber isolator in between the plates. The modeling and assembly of rubber mount components is done using I-DEAS and finite element structural analysis and numerical investigation are made on the finite element (FE) analysis software ABAQUS. The deformations of rubber mount obtained from FE analysis are used in the Minitab to develop the mathematical model and deformations are obtained with respect to different process parameters. The results obtained from the predicted model are compared with the numerical simulation results.

Keywords: Engine mount; Rubber; Finite Element Analysis (FEA);RSM.

1. Introduction

The present scenario of automobile industries is improving the performance of vehicles by providing fuel efficient engine and riding comfort. The comfort of vehicle riding depends upon how smoothly an engine operates and how effectively the engine vibration forces are isolated between the engine and the chassis. Two main sources of engine vibration are combustion pressure and fluctuating forces from engine rotating and reciprocating components [5]. The engine unbalanced forces are isolated by balancing the forces in the engine itself and providing the vibration dampers in the chassis. The elastomeric mounts are the vibration dampers are acting as supporting structures as well as vibration dampers. Engine mounts properly locate the engine in the chassis and reduce the vibration forces transmitted from the engine unbalanced forces.

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Nomenclature

r	Rubber Thickness in mm
t	Top Plate Thickness in mm
b	Bottom Plate Thickness in mm
l	Load Applied in N
d	Inclination in degrees
k	Number of factors
Y	Estimated value
β_i	Regression coefficient of i[th] independent variable
β_{ij}	Regression coefficient of interaction of i[th] independent variable
$\hat{\beta}_i$	Estimated value of β_i
$\hat{\beta}_{ij}$	Estimated value of β_{ij}

Elastomeric material usually has long chain molecules recognized as polymers. The term elastomer is the combination of elastic and polymer and is often used interchangeably with the rubber .The rubber component as an engineering material has been used in automotives as engine mountings, tires, vibration isolators and oil seals [1]**.** The rubber mounts are compact, cost-effective and maintenance free the mounts have been successfully used for vehicle engine mounts for many years [4].The type of rubber used in the mount is natural rubber which is an elastic hydrocarbon polymer that naturally occurs as a milky colloidal suspension, or latex, in the sap of some plants [12]. In its crude form, it has poor mechanical properties. Natural rubber, like many of the synthetic rubbers, is converted into usable products through compounding with additives and subsequent vulcanization which is a process of heating rubber with sulphur that makes rubber harder and stronger and at the same time retaining its elasticity [6]. Natural rubbers have good electrical properties, excellent resilience, and tear resistance. They soften with exposure to sunlight and when in contact with certain organic solvents and some strong acids. The tear resistance and low hysteresis (heat build-up on flexure) make natural rubbers prime candidates for shock absorbing parts [7]. Natural rubber is susceptible to oxidation. This can affect both the processing qualities of the rubber and also the final compounded rubber mechanical properties. Natural antioxidants will offer protection to degradation of natural rubber [5]. Natural rubbers have good resistance to cutting, gouging and abrasion. They have density of about 930 kg/m^3, tensile strength of 17.2 – 24.1*10^6 N/mm^2, elongation of 500 – 760%. Its useful temperature range is -60 – 120 degree Celsius [6].

The finite element method is followed to find out the deformation. In the finite element method the actual continuum or body of the matter is represented by an assemblage of subdivisions called finite elements. These elements are considered to be interconnected at specified joints called nodes or nodal points. The nodes usually lay on the element boundaries where adjacent elements are considered to be connected [9]. The properties of the materials in each element and the boundary conditions are specified. By specifying different properties of the materials for different finite elements, an object comprising regions of numerous materials can be analyzed. The sum total of behaviour of the individual elements gives the behaviour of the continuum. Different element type can be utilized and the mesh size can be varied, and it is simple to change loads, materials, and geometry for a modified structure.

This paper describes the methods of predicting the deformation in the mount to optimize the geometric characterisation of the engine mount structural components by defining real design variables cross-section properties of mount elements [3]. Previous models have been referred to design the mount. Modeling of the mount is done using the I-DEAS and the finite element analysis (numerical experimentation) of the modelled rubber mount is done to determine the deformation by the ABAQUS. The predication of the mathematical model is to find the deformation to meet the required stiffness of the mount in shear mode. The comptation has been carried out by using MINITAB, which is statistical software. Regression analysis was employed to develop mathematical model and Analysis of Variance (ANOVA) was used to test their adequacy. The effects of control parameters (rubber thickness, top plate thickness, bottom plate thickness, load applied and inclination) on deformation have been studied in detail. The schemes of approaches followed in this paper are identification of factors, finite element analysis, developing mathematical model, testing the adequacy of the model, response surface analysis and conclusions.

2. FINITE ELEMENT ANALYSIS

The finite element analysis of the rubber mount has been carried out using the ABAQUS. The mount is modeled in the IDEAS and the modeled mount characteristics are imported to FE software to determine the deformation. The mount modeled has the limiting dimensions of 200(Length) mm by 70(Height or thickness)mm by 60(Width) mm.The static stiffness in shear mode is to be 100N/mm.The engine mounts are to be mounted at an angle of 30 to 45 degrees. The model is created in the modeling software I-deas version 11. The model is then imported to the finite element analysis software Abaqus. Input parameters: The material properties are given, element type assigned and meshing is done in this software. The static structural analysis is performed after giving the boundary conditions and load. The top and bottom plates are of mild steel for which the material property is isotropic. Young's Modulus =2.1e5 N/mm^2. Poisson Ratio = 0.3. The isolator used in between the plates is Natural Rubber whose material property is hyper elastic. Based on the test data of the material, the strain energy potential coefficients are obtained as 0.5507, -0.3197, and 0.2002. The element type is given as 8 node brick, hybrid element. The length and width of the rubber have been kept as 65mm and 50mm respectively for all the analysis but the thickness alone is varied. Output: The resultant value of deformation is taken for the values of the given input parameters. The values of the dimensions of the top plate thickness, bottom plate thickness, rubber thickness, load applied and the inclination of the mounting are varied and the corresponding values of deformation are taken. The values or dimensions for the parameters are selected using the Response Surface Methodology. A set of dimensions can then be selected to meet the required stiffness. The output results (Deformation) of the finite element analysis for various values of rubber thickness (r), top plate thickness (t), bottom plate thickness (b), load applied(l) and inclination (d).

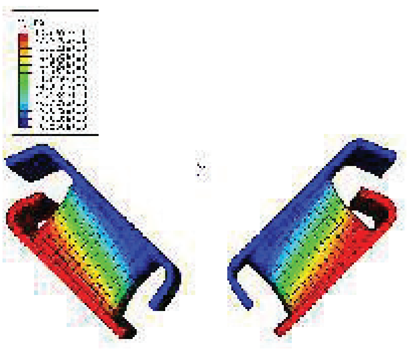

Fig.1 Deformation from finite element analysis for r=46mm, t=4.5mm, b=4.5mm, l=2900N, d=40 deg.

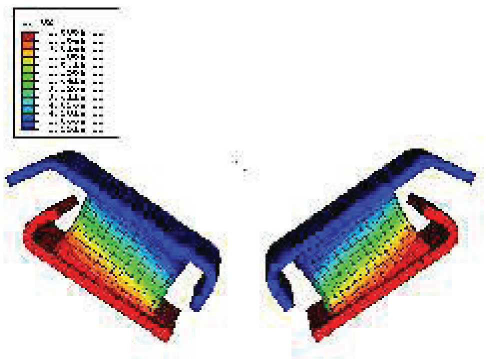

Fig.2 Deformation from finite element analysis for r=42mm, t=5.5mm, b=5.5mm, l=2500N, d=35 deg

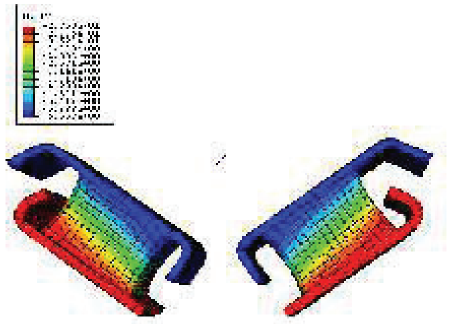

Fig.3 Deformation from finite element analysis for r=46mm, t=4.5mm, b=5.5mm, l=2500N, d=35 deg.

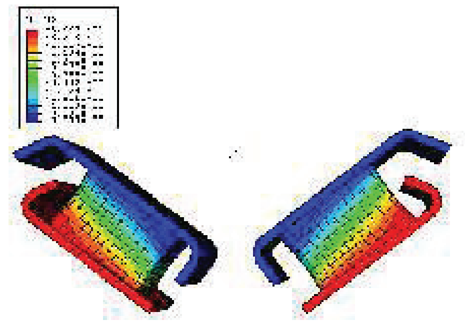

Fig.4 Deformation from finite element analysis for r=44mm, t=5mm, b=5mm, l=3100N, d=37 deg.

3. Experimental Design and Procedure

3.1 Identification of predominant factors

In the present investigation, the process parameters, namely, the rubber thickness (r), top plate thickness (t), bottom plate thickness (b), load applied (l) and inclination of the mount (d) were identified as the main factors influencing the deformation of the engine mount. The key factor in developing a mathematical model is to obtain sufficient data from the finite element experimentation. To reduce the total number of experiments and to obtain data uniformly from all the regions of the working area, a factorial design procedure has been adopted. The analysis was carried out using actual values

Table 1 - Levels and Values of Parameters

Parameter/ Notations/ Units	Parameter Levels				
	-2	**-1**	**0**	**1**	**2**
Rubber (r) mm	40	42	44	46	48
Top Plate (t) mm	4	4.5	5	5.5	6
Bottom Plate (b) mm	4	4.5	5	5.5	6
Load(l) Newtons	2300	2500	2700	2900	3100
Inclination (d) degrees	30	35	37	40	45

The selection of the limits of the process variables is followed by choosing the number of levels within the limits

3.2 Experimental design matrix

In order to optimize the process, Central composite rotatable design of second order Response Surface Methodology, a full factorial design is established which takes into account all the possible combinations of process parameters. It establishes the mathematical relation of the response surface using the smallest possible number of experiments without losing its accuracy. Table 1 shows the parameter settings for performing the statistical test on degree of significance of process parameters and their interactions. The selected design matrix, shown in Table 2, Table 3, and Table 4 is a five factor five level central composite rotatable design consisting of 52 sets of coded conditions.

Design Matrix Values and Responses

Table 2: Coded values of parameters

Sl no	Rubber thick-ness (x_1)	Top plate thick ness (x_2)	Bottom plate thick ness (x_3)	Load applied (x_4)	Inclination (x_5)
1.	1	1	-1	1	-1
2.	-1	-1	-1	-1	-1
3.	0	0	0	0	0
4.	-1	-1	-1	1	1
5.	-1	-1	1	1	1
6.	-1	1	-1	-1	1
7.	0	0	0	0	0
8.	-1	1	1	-1	1
9.	-1	1	1	1	-1
10.	1	-1	-1	-1	1
11.	-1	1	-1	1	1
12.	1	-1	1	-1	-1
13.	-1	1	-1	-1	-1
14.	0	0	0	0	0
15.	1	-1	1	-1	1
16.	1	1	1	1	-1
17.	1	-1	1	1	1
18.	0	0	0	0	-2
19.	2	0	0	0	0
20.	1	1	1	1	1
21.	1	-1	-1	-1	-1
22.	1	-1	-1	1	1
23.	0	0	0	0	0
24.	-1	1	1	-1	-1
25.	0	0	0	0	0
26.	-1	1	-1	1	-1
27.	-1	1	1	1	1
28.	1	1	-1	1	1
29.	0	0	0	2	0
30.	0	0	0	0	0
31.	-1	-1	-1	-1	1
32.	1	1	-1	-1	-1
33.	1	1	1	-1	-1
34.	-1	-1	1	-1	-1
35.	0	0	0	-2	0
36.	0	0	0	0	0
37.	0	-2	0	0	0
38.	0	0	2	0	0
39.	-1	-1	1	1	-1
40.	1	1	1	-1	1
41.	0	0	0	0	0
42.	0	0	0	0	0
43.	0	0	0	0	2
44.	1	-1	1	1	-1
45.	0	0	-2	0	0
46.	1	-1	-1	1	-1
47.	-1	-1	1	-1	1
48.	1	1	-1	-1	1
49.	0	2	0	0	0
50.	0	0	0	0	0
51.	-2	0	0	0	0
52.	-1	-1	-1	1	-1

Table 3: Actual values of parameters

Sl.No	Rubber thick-ness (r) mm	Top plate thick-ness (t) mm	Bottom plate thick-ness (b) mm	Load applied (l) N	Inclination (d) in degrees
1.	46	5.5	4.5	2900	35
2.	42	4.5	4.5	2500	35
3.	44	5	5	2700	37
4.	42	4.5	4.5	2900	40
5.	42	4.5	5.5	2900	40
6.	42	5.5	4.5	2500	40
7.	44	5	5	2700	37
8.	42	5.5	5.5	2500	40
9.	42	5.5	5.5	2900	35
10.	46	4.5	4.5	2500	40
11.	42	5.5	4.5	2900	40
12.	46	4.5	5.5	2500	35
13.	42	5.5	4.5	2500	35
14.	44	5	5	2700	37
15.	46	4.5	5.5	2500	40
16.	46	5.5	5.5	2900	35
17.	46	4.5	5.5	2900	40
18.	44	5	5	2700	30
19.	48	5	5	2700	37
20.	46	5.5	5.5	2900	40
21.	46	4.5	4.5	2500	35
22.	46	4.5	4.5	2900	40
23.	44	5	5	2700	37
24.	42	5.5	5.5	2500	35
25.	44	5	5	2700	37
26.	42	5.5	4.5	2900	35
27.	42	5.5	5.5	2900	40
28.	46	5.5	4.5	2900	40
29.	44	5	5	3100	37
30.	44	5	5	2700	37
31.	42	4.5	4.5	2500	40
32.	46	5.5	4.5	2500	35
33.	46	5.5	5.5	2500	35
34.	42	4.5	5.5	2500	35
35.	44	5	5	2300	37
36.	44	5	5	2700	37
37.	44	4	5	2700	37
38.	44	5	6	2700	37
39.	42	4.5	5.5	2900	35
40.	46	5.5	5.5	2500	40
41.	44	5	5	2700	37
42.	44	5	5	2700	37
43.	44	5	5	2700	45
44.	46	4.5	5.5	2900	35
45.	44	5	4	2700	37
46.	46	4.5	4.5	2900	35
47.	42	4.5	5.5	2500	40
48.	46	5.5	4.5	2500	40
49.	44	6	5	2700	37
50.	44	5	5	2700	37
51.	40	5	5	2700	37
52.	42	4.5	4.5	2900	35

4. Mathematical Modeling By Response Surface Methodology

4.1 Theoretical Aspects

For five independent variables x_1, x_2, x_3, x_4 and x_5, the response Y can be represented as a function of x_1, x_2, x_3, x_4 and x_5 as follows [8]

$$Y = f(x_1, x_2, x_3, x_4, x_5) + \varepsilon \tag{1}$$

where ε represents an error component.

The second order RSM model is adequate which can be represented by the following equation.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i,j}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

where β_I (i= 0, 1,……….p) are coefficients that have to be estimated and ε represents a normally distributed random error that accounts for all source of variability.
The fitted equation is represented by

$$Y = E(Y - \varepsilon)$$

$$Y = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_{ii} x_i^2 + + \sum_{i,j}^{k} \hat{\beta}_{ij} x_i x_j \tag{3}$$

where $\hat{\beta}_0$ is the estimator of intercept, $\hat{\beta}_1$, $\hat{\beta}_2$... β_k are linear terms, $\hat{\beta}_{11}$, $\hat{\beta}_{22}$... $\hat{\beta}_{kk}$ are quadratic terms, and $\hat{\beta}_{12}$, $\hat{\beta}_{13}$... $\hat{\beta}_{k-1,k}$ are the second order interaction terms.

The response function representing the deformation can be expressed as,

Y = f {Rubber thickness (r), top plate thickness (t), bottom plate thickness (b), load applied (l), and inclination of the mount (d)}

$$Y = f(r, t, b, l, d) \tag{4}$$

where Y is response or yield.

For five factors, the selected polynomial could be expressed as follows

$$\begin{aligned} Y = {} & \hat{\beta}_0 + \hat{\beta}_1 *r + \hat{\beta}_2 *t + \hat{\beta}_3 *b + \hat{\beta}_4 *l + \hat{\beta}_5 *d + \hat{\beta}_{11} *r_2 + \hat{\beta}_{22} *t_2 + \hat{\beta}_{33} *b_2 + \hat{\beta}_{55} *d_2 + \hat{\beta}_{12} *r*t \\ & + \hat{\beta}_{13} *r*b + \hat{\beta}_{15} *r*d + \hat{\beta}_{23} * t*b + \hat{\beta}_{25} *t*d + \hat{\beta}_{35} *b*d + \hat{\beta}_{45} *l*d \end{aligned} \tag{5}$$

4.2 Estimation of coefficients of models and their significance

The values of the coefficients of the polynomial were calculated by regression method and were reported in Table 5. The magnitude of the regression coefficient is a good indication of the significance of the parameters.The finite element analysis data were analyzed using the software MINITAB which gives the output in tabular form and was used to calculate the values of these coefficients. For the required response, all the 52 observed values and the second order general mathematical model for the five factors are given to the software as input. The significance of the coefficients was evaluated.

Table 5: Coefficient values for deformation

Values of the Coeffcients			
β_0	24.9375	β_{12}	-0.0109
β_1	-0.6172	β_{13}	-0.0013
β_2	+0.6682	β_{14}	+0.0001
β_3	+0.1630	β_{15}	+0.0063
β_4	-0.0059	β_{23}	-0.0048
β_5	-0.6037	β_{24}	-0.0000
β_{11}	+0.0046	β_{25}	-0.0018
β_{22}	-0.0075	β_{34}	-0.0000
β_{33}	-0.0085	β_{35}	+0.0001
β_{44}	0.0000	β_{45}	+0.0001
β_{55}	0.0038		

4.3 Final model of the design matrix

The final mathematical model as determined by above analysis in natural scale is given below

$$\begin{aligned} Deformation = {} & 24.9375 - (0.6172*r) +(0.6682*t) +(0.1630*b) - (0.0059*l) \\ & -(0.6037*d) + (0.0046* r2) - 0.0075*t2) - (0.0085* b2) +(0.0038*d2) \\ & - (0.0109*r * t) - (0.0013*r*b) + (0.0001*r*l) + (0.0063*r*d) \\ & - (0.0048*t*b) - (0.0018*t*d) + (0.0001*b*d) + (0.0001*l*d) \end{aligned}$$

where r – rubber thickness, t – top plate thickness, b – bottom plate thickness, l – load applied, and d – inclination of the mount.

This equation is called a response surface and it could be used to predict the deformation.

4.4 Checking the adequacy of the developed Model

Table: 6 Analysis of Variance for deformation

Source of variation	DF	Seq SS	Adj SS	Adj MS	F-test
Regression	20	32.14	32.14	1.607	2E+4
Linear	5	31.90	.1015	.0203	201.9
Square	5	0.087	.0870	.0174	173.1
Interaction	10	0.155	.1549	.0155	154.1
Residual error	31	0.0031	.0031	.0001	
Lack of fit	22	0.0031	.0031	.0001	
Pure error	9	0.0000	.0000	.0000	
Total	51	32.15			

Significant at the 5% level, SS-Sum of Squares, DF-Degrees of Freedom, MS-Mean Square, F-ratio = M.S lack of fit / M.S of error,

$$F\ (20, 9, 0.005) = 2.94, \quad F\ (\text{table value}) = 2E+4$$

The analysis of variance for this second order regression model was calculated with aid of the software MINITAB The deformation has been mainly influenced by linear terms (201.9) followed by square terms (173.1) and interaction terms (154.1). The test of adequacy for the predicting response surface equations has been carried out by Fisher's variance ratio test known as F-test. As per this technique, the estimated F- values for the predicting equations are much greater than 2.94. Hence, it is assured that the established predicting equation gives an excellent fitting to the observed data for a confidence level of 95%.

4.5 Conformity test

The finite element analysis result was compared with that of the experimental result. One deformation result of the experiment was compared with the FEA result after which the deformation values for various dimensions have been taken using finite element analysis.

Table: 7 Conformity of the model

Response (Parameters: r=36mm,t=5mm, b=5mm,l=2900N, d=45 degrees)	Experimental value	FEA result	Error %
Deformation in mm	10.2	9.49	6.96

5. Conclusion

- The effect of various parameters, namely, the rubber thickness (r), top plate thickness (t), bottom plate thickness (b), and load applied (l) and the inclination of the mounts (d) on deformation of the mounts has been studied based on the developed mathematical model.

- A statistical analysis has been performed to study the individual as well as interaction effect of parameters on deformation and has been found that the individual effects are highly significant.

- The adequacy of the model has been tested by F-test, which indicates that the developed response surface equation is in good agreement with the observed data.

- The Finite element analysis result as compared with that of the experimental result to validate the result of the finite element analysis.

- Also there is a good convergence between the finite element analysis and the mathematical model, the mathematical model possesses high prediction ability in practical situations.

- As the model is created in modeling software and exported to the analysis software, there are chances for the data losses. This leads to the error between the experiment values and finite element analysis values.

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